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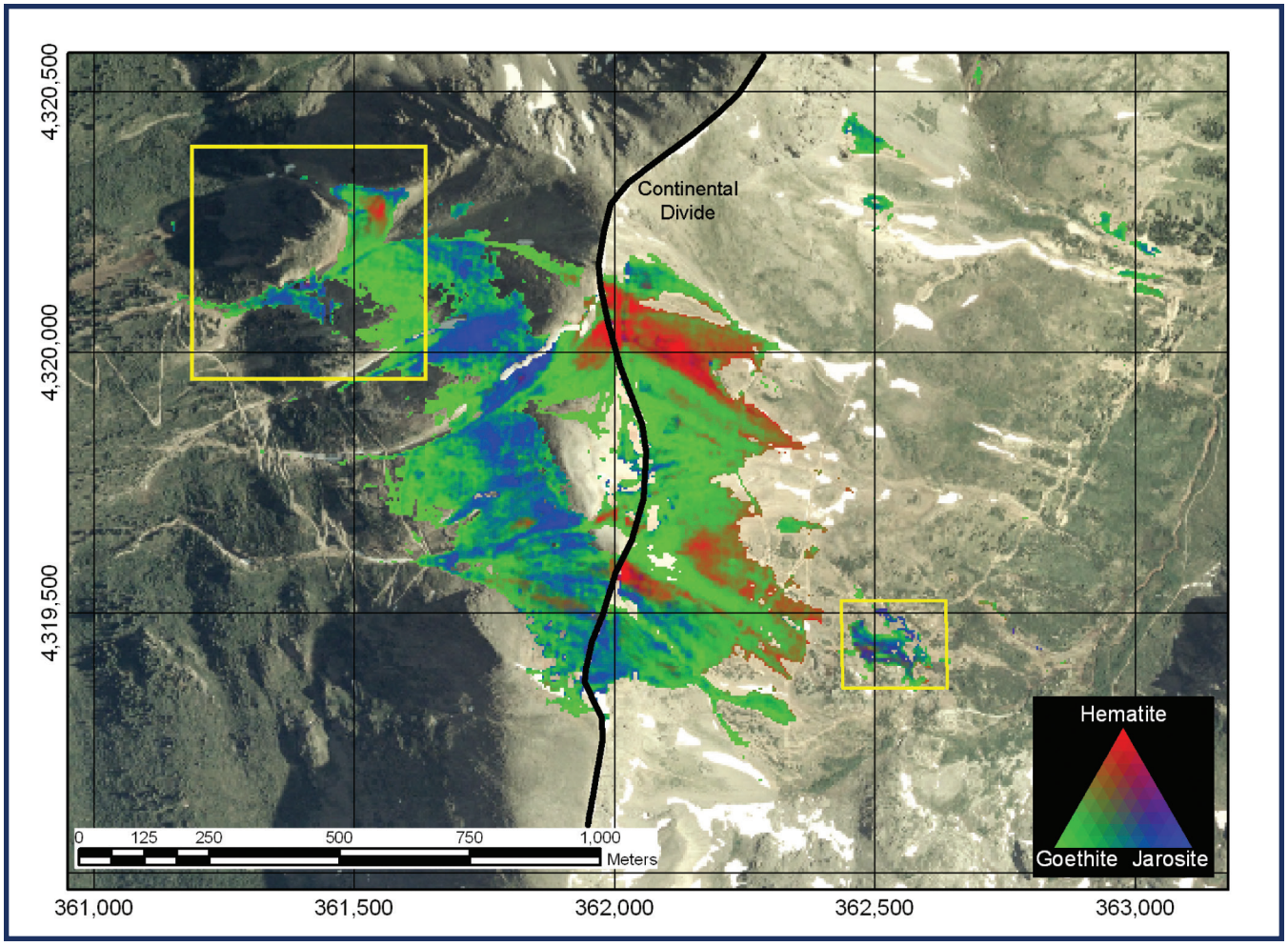
REMOTE SENSING AND SPECTRAL GEOLOGY



Editors
R. Bedell, A.P. Crósta, and E. Grunsky

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Remote Sensing and Spectral Geology

R. Bedell, A.P. Crósta, and E. Grunsky, Editors

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Hamid Ali-Ammar graduated with a degree as a geologic engineer from the University of Alger, Algeria. After further specializing at the University of Paris VI in France, he conducted four years of doctoral research at the University of Orleans, France, in the field of lead-zinc metallogeny in northeastern Algeria. He joined University of Liege, Belgium, in 2002, focusing on multispectral remote sensing of salt lakes in the Andes cordillera.

Neivaldo Araujo De Castro graduated with a degree in geology from the Federal University of Parana (UFPR) in 1993. His M.Sc. work was in metallogeny, focusing on mineral exploration of Neoproterozoic granitoids of the Dom Feliciano belt, Santa Catarina, Brazil, at the State University of Campinas (UNICAMP). Subsequent work was in quality control and pre-processing airborne surveys for The Lasa Engenharia E Prospecções Ltda during late 1990s. A Ph.D. degree followed, in 2005, at São Paulo University (USP), where Araujo de Castro worked on geologic mapping, petrography, lithogeochemistry, and geochronology in Neoproterozoic terranes of the Borborema Province, northeast Brazil. From 2001 until 2005, he was a consultant in geophysics and mineral exploration for companies that included Gold Fields and Pan Brazilian Mineração. Postdoctoral research at the Federal University of Minas Gerais (UFMG) in 2006 focused on high-resolution airborne geophysics and geology in the southwestern portion of São Francisco craton. Currently, he is an adjunct professor at the Federal University of Ceará (UFC) and works in the systematic geologic mapping program of the Brazilian Geological Survey (CPRM).

Zan L. Aslett is a Ph.D. candidate in geophysics at the University of Nevada. His research focuses on the analysis of ground, aerial, and spaceborne hyperspectral image data measurements in the visible through thermal infrared spectrum to remotely identify surface mineralogy and man-made materials. His work is funded by the National Nuclear Security Administration's NA-22 program in order to further use this type of data to remotely monitor and characterize geologic aspects of nuclear proliferation activities.

Francisco "Chico" Azevedo is currently exploration manager for South America with Gold Fields Exploration. He earned a B.Sc. degree in geology from the University of Brasilia (1982) and started his career as an exploration geologist with GENCOR in Brazil, where he worked for 12 years, before being transferred to Argentina in 1994. In 1996 Chico joined IAMGOLD Corporation in Argentina as exploration manager, and was in charge of implementing and managing the exploration programs there until 2006. He joined Gold Fields in 2006 in his current position. Chico is Regional VP Latin America for the Society of Economic Geologists.

Franciscus Jacobus Baars is a Dutch geologist who was born and educated in South Africa and now is a permanent resident of Brazil with an M.Sc. in metamorphic geology from the University of Cape Town under Dr. John Moore. He has performed geologic cartography of four sheets at a 1:100,000 scale in the Espinhaço Range and worked broadly in Brazil and shield, South America, mainly on exploration geology for De Beers Consolidated, Companhia Vale do Rio Doce-Vale. As an independent consultant, he worked for, among others, the Brazilian Geological Survey, Companhia de Pesquisa de Recursos Minerais, Pan Brazilian, Minmet, Caraíba Metais, Gold Fields, Eldorado Gold Corp., Lara Exploration, IMS–Jaguar Resources, EBX, GME4–Global Minerals Exploration, Engenharia de Recursos Minerais, MMX, Fundação Gorceix, Kinross, BHP-Billiton Metals, Anglogold Ashanti, Mineração Santa Blandina, and Amarillo Gold. This work covered a broad range of commodities, including gold, diamonds, iron, manganese, alumina, base metals, PGM, Ni, rutile, Ti, kaolin, phosphate, and potash. At the Survey, Mr. Baars coordinated the conceptual GIS plan and the mineral resource compilation, as a key fourth author for the 1:2,500,000 Geological, Mineral Resources and Geotectonic of Brazil-published in 4 sheets and in DVD-GIS format with some 210 co-authors. He authored a chapter on the São Francisco craton in the 1995 Oxford University Press volume on Greenstone Belts and has coauthored a number of peer-reviewed papers most particularly focusing on the metallogenic evolution of the Carajás mineral province.

Richard L. Bedell Jr. is co-founder, director, and executive vice president of AuEx Ventures, a gold exploration company listed on the Toronto Stock Exchange, and adjunct faculty in exploration geophysics at the Mackay School of Earth Sciences and Engineering in Reno, Nevada. Previously he worked with Homestake Mining as part of the global target selection team and ran the technical group worldwide for exploration. Other experience includes positions as exploration manager for the Burundi Mining Company, a research geologist for BP Minerals International in London, RioCanex Exploration Party Chief, geologist, Dar Tadine, Tanzania. Academic appointments include the following: director of the GIS Center at Boston College, assistant professor at the Remote Sensing Center at Boston University, and research geologist in meteoritics at the American Museum of Natural History in New York City. Education includes a BA from Hampshire College in Massachusetts, from the school of Natural Sciences & Mathematics, with a thesis on sulfide-oxide equilibria in the Earth's mantle; an M.Sc. at the University of Toronto in economic geology with a thesis on the uraniferous pegmatites of the Bancroft district in Ontario, Canada; a second M.Sc. was obtained at the University of London in remote sensing and GIS with a thesis on edge detection and enhancement of Archean lode gold deposits of the Mara gold district in Tanzania.

Colin G. Brodie is a senior consulting geologist based in Mendoza, Argentina. He received both his B.Sc. and M.Sc. degrees in geology from the University of Otago, New Zealand (1979 and 1985, respectively) and a Post Graduate Diploma in GIS from the University of Leeds, UK (2003). He has worked as a geologist for about 25 years, initially with the New Zealand government on mapping projects in Antarctica, but mainly in the mining-exploration industry, with a special

interest in applications of GIS and remote sensing to mineral exploration.

Michael Caccetta received his bachelor of science degree in computer science from Curtin University, Western Australia, in 1994. Since joining the Division of Exploration and Mining, CSIRO, in 1997, he has been primarily involved in the processing of remotely sensed and GIS data for mining industry research projects. His skills and interests include image processing, hyperspectral data analysis, geographical information systems, algorithm development, and data visualization. His most recent work has been focused on developing methods and software for the processing of large volume, multiscene airborne and satellite radiance data to accurate mineral map mosaics.

F. Caceres-Jerez graduated as geologic engineer from the Universidad Tecnica de Oruro, Bolivia. After having worked as an exploration geologist for gold mineralization in the Precambrian shield, he specialized at University of Liege, Belgium, in remote sensing and geologic information systems for mineral exploration. After three years of Ph.D. research, exploring the potential of ASTER VNIR-SWIR images, he took the lead in a research project on environmental impact assessment of mining and industrial activities using hyperspectral airborne imaging (AHS sensor).

Fabio Cardinale Branco received a B.A. degree in geology in 1992 from São Paulo University, Brazil, and an M.S. degree in geology in 1998 from São Paulo University. He has worked for an environmental consulting company in Brazil since 1996, becoming one of the general managers. Research interests have focused on remote sensing, environmental planning and impact, and environmental control of air pollution generated by cars in large cities in Brazil.

Philip Connor is an electrical engineer who received his undergraduate degree from Sydney University in 1973 and then a master's degree in electrical engineering and computer science from the University of New South Wales in 1982. He worked for seven years at Macquarie University conducting research into speech and music using Fourier analysis and the development of a fast digital signal processor before joining the CSIRO in 1991. At CSIRO he has been developing infrared and thermal infrared airborne, laboratory, and drill core electro-optical instruments for the measurement of minerals for the mining industry. This includes the design and development of the optics and real-time software of a series of multituned laser, grating/array, and Fourier transform spectrometers such as the MIRACO2LAS, OARS, Hychips™, Hylogger™, and TIRLogger™ instruments. Philip's other interests apart from his work at CSIRO have included solar energy, which led to his development of the Liquid Solar Array method, which is now patented.

Mark F. Coolbaugh is a research assistant professor at the Great Basin Center for Geothermal Energy and the Arthur Brant Laboratory for Exploration Geophysics at the University of Nevada, Reno. For the last eight years Dr. Coolbaugh has been conducting geothermal research using thermal infrared remote sensing, spatial analysis in geographic information systems, geologic mapping, and structural analysis. He has also served as chief geoscientist, chief geologist, and exploration manager for a number of metals and geothermal exploration companies in the United States, Asia, and Central America. Dr. Coolbaugh received a B.Sc. degree in geological engineering from Colorado School of Mines, an M.Sc. degree in geological engineering from the University of Arizona, and a Ph.D. degree in geology from the University of Nevada, Reno.

David W. Coulter has been involved in the use of multispectral and hyperspectral imagery for mineral exploration and environmental monitoring for over 25 years. He received a B.S. degree in geology from Kent State University, an M.S. degree in geologic engineering from University of Arizona, and a Ph.D. degree in interdisciplinary geology and geophysics from the Colorado School of Mines. He was responsible for remote sensing and image processing at Newmont Mining Corporation from 1984 to 2001 and has been a researcher and scientist on publicly funded and commercial projects from 2001 to the present. His interest focuses on the use of airborne and satellite imagery for the remote identification and mapping of minerals and their relationship to ore-forming processes.

Alvaro P. Crósta is a full professor of geology, Institute of Geosciences, University of Campinas, Brazil. Currently, he is director of the Geosciences Institute, UNICAMP. Dr. Crósta earned a B.Sc. degree in geology from the University of São Paulo, 1977, an MSc. degree in remote sensing from the Brazilian Institute of Space Research, 1982, and Ph.D. degree in geological remote sensing from Imperial College, University of London, UK, 1990. From 1995 to 1996 he was a visiting scientist at the Desert Research Institute, Reno, Nevada. He acts as referee of the journals International Journal of Remote Sensing, Computer & Geosciences, Annals of the Brazilian Academy of Sciences, Meteoritics & Planetary Science, and several Brazilian scientific journals. Main research areas include remote sensing applied to mineral and petroleum exploration, meteoritic impact craters, and geotechnologies.

Thomas Cudahy is a geologist and leader of CSIRO's Minerals and Environmental Sensing Group. He has an undergraduate degree (with Honours) in structural geology from Macquarie University (1984) and a Ph.D. from Curtin University (2000) with a thesis based on thermal infrared silicate and surface scattering mapping using an airborne multi-line CO_2 laser. In his 25-year career with CSIRO, Dr. Cudahy has led numerous national and international collaborative research projects and been a member of various satellite science teams, including ASTER and Hyperion. He has also worked with airborne SEBASS, HyMap™, ARGUS, and Geoscan™ data, from instrument calibration through to validation and mineral systems analysis of derived geoscience

products. He is also the proposed Director for a new Western Australian Centre of Excellence for 3-D Mineral Mapping (C3DMM) which, in collaboration with the government geoscience agencies, is developing capabilities that will ultimately deliver a web-accessible 3-D mineral map of the Australian continent based on surface (remote sensing) and subsurface (drill core) hyperspectral technologies.

Diego A. Ducart is an exploration geologist with Hochschild Mining Company, Mendoza, Argentina. He received a B.Sc. degree in geology (2001) from the National University of Rio Cuarto, Argentina, an M.Sc. degree (2004) and a Ph.D. (2007) in remote sensing from the Institute of Geosciences, University of Campinas (UNICAMP), Brazil. He was a visiting scientist at the Stable Isotope Laboratory and at the Remote Sensing and Spectroscopy Lab at the U.S. Geological Survey in Denver, Colorado (2006). Dr. Ducart's main areas of interest include remote sensing and geotechnologies applied to mineral exploration, and hydrothermal alteration.

Eric C. Grunsky is currently with the Geological Survey of Canada. He is a graduate of the University of Toronto (B.Sc., 1973; M.Sc., 1978) and the University of Ottawa (Ph.D., 1988). Eric's background is in geological field mapping and numerical geology, including the interpretation of geochemical survey data, the use of remote sensing in mapping programs, resource assessment methodologies, and geoscience information management strategies. He has worked for CSIRO (Western Australia), provincial geological surveys in Alberta, British Columbia, and Ontario, and has been a consultant to the mineral exploration industry in the interpretation of geochemical data and the use of remotely sensed imagery. Recently, Eric has been using combined optical and multi-angle radar remotely sensed imagery to refine surface materials mapping as part of the Remote Predictive Mapping Project for mapping Canada's North.Eric is an adjunct professor at Laurentian University, Sudbury, Ontario. He is currently editor-in-chief for the international journal, Computers & Geosciences, and serves on the editorial boards of several journals: Geochemistry, Analysis, Exploration, Environment and Exploration and Mining Geology.

Rob Hewson is a geophysicist who completed his undergraduate science degree (with Honours) at Melbourne University before working for Shell Australia for seven years. He then completed a master of science degree (with Honours) in geophysics at Macquarie University, followed by a Ph.D. at the University of New South Wales on geologic remote sensing using chiefly thermal infrared systems. He then worked as a geophysicist with the NSW Geological Survey before joining CSIRO as a research scientist in 1998. Since joining CSIRO, he has worked as a remote sensing geoscientist on geologic case study investigations of ASTER satellite and airborne hyperspectral data. Rob is also responsible for the calibration and validation of the Group's laboratory and field spectrometers and is conducting detailed spectroscopic studies of mineralogy, especially at thermal infrared wavelengths.

Jon Huntington has been involved in field, airborne, and spaceborne geologic remote sensing and image processing for most of his 34-year CSIRO career, in particular championing imaging spectroscopy for characterizing host rock, alteration, and regolith mineral composition for the exploration and mining industry. His research has included leading spectral sensing technology developments and characterizing the alteration mineralogy and mineral chemistry of a wide variety of mineral systems, through numerous AMIRA and industry-funded research projects. He was a part of the original PIMA™ prototype development team, codeveloper of The Spectral Geologist (TSG™) software package, and instigator of the HyLogging™ automated core-logging and AuScope National Virtual Core Library concepts. He is a Fellow of the Australian Academy of Technological Sciences and Engineering and focuses most of his current research on behalf of the CSIRO Division of Exploration and Mining.

Caetano Juliani received a B.A. degree in geology in 1980 from the Geosciences Institute of the Paulista State University, Brazil, and a Ph.D. degree from the Geosciences Institute of São Paulo University in 1993. He was geologist of the São Paulo Institute of Technology from 1981 to 1987. He has been a professor at the São Paulo University since 1988 and full professor since 2002. Research interests have focused on crustal evolution of Precambrian terranes, metamorphic petrology, fluid-rock interaction, hydrothermal alteration, and gold and base metals metallogenesis in volcano-sedimentary sequences, especially in Paleoproterozoic unmetamorphosed epithermal and porphyry-type mineralization in Amazonian craton.

Eric Pirard is professor of mineral resources characterization at University of Liège and head of the GeMMe—Minerals Engineering, Materials and Environment—department. He holds a Ph.D. in mathematical morphology and has more than 20 years experience in applying digital image analysis to important issues in applied geology and mineralogy: shape and size distribution of particles, quantitative microscopy, online quality control of ornamental stones, close and remote sensing of geologic outcrops, etc. Dr. Pirard is vice president of the Commission for Applied Mineralogy and acted as convenor of several congresses in quantitative geology (Geovision 99; Mathematical Geology 06). He is also member of the board of the International Society for Stereology and Image Analysis (ISS). During the last years he has been teaching applied image analysis to geologists and mineralogists at several major universities (Paris, Nancy, Firenze, Madrid, Lima). He is a founding member of OCCHIO Instruments, a company that manufactures innovative imaging technology for particle characterization.

Melissa Quigley is a Research Scientist and Geologist within the Mine and Environment Spectral Sensing Group of Australia's CSIRO Division of Exploration and Mining. Melissa gained a bachelor of information technology (spatial information systems) in 1999 from Charles Sturt University and a master of science (geology) (Honours 1st class) in 2004

from Macquarie University. During her nine years with CSIRO, Melissa has developed specialist knowledge and skills in the acquisition, analysis, and interpretation of hyperspectral data for mineralogical information extraction. These skills have been applied to data acquired from spaceborne (e.g., Hyperion), airborne (e.g., HyMap™), and field-based instruments (e.g., PIMA™ and ASD™). With the current development of CSIRO's suite of HyLogger™ core-logging systems, Melissa's skills are now applied at the mine scale for hyperspectral data collected from drill core and chips to aid deposit characterization and mineral exploration. Through her work she has gained broad exposure and understanding of different mineral deposit types ranging from Archean gold, Proterozoic base metals, and Cambrian Cu-Au volcanic-hosted sulfide deposits.

Teodoro I. Ribeiro de Almeida received a B.A. degree in geology from São Paulo University (USP), Brazil, in 1977, an M.S. degree in 1982 from National Institute of Spatial Researches-Brazil, and a Ph.D. degree from the Geosciences Institute of São Paulo University in 1991. He worked as a geologist for Votorantim Group, a major mining company in Brazil, from 1980 to 1990. He joined the Geosciences Institute at USP as faculty in 1991 and became a full professor in 2005. His research interests are broad but primarily involve mineral exploration and remote sensing. Over the past several years, his work has focused on developing techniques for the study of the geologic influence on vegetation spectral behavior. Recently, he has also done a biogeochemistry study in the Pantanal Wetlands in Western Brazil.

Benoit Rivard received the Ph.D. degree in earth and planetary sciences from Washington University, St. Louis, Missouri, in 1990. He is currently a professor at the department of Earth and Atmospheric Sciences of the University of Alberta. Dr.Rivard is a geologist with particular interest in the development of applied geologic remote sensing. His key research focus is to develop the analysis of hyperspectral sensing (field, airborne, and spaceborne) to improve the effectiveness of the oil and mining industries and mapping agencies to delineate and manage their targeted resources. In this respect he has been working to do the following: (1) automate the hyperspectral analysis of rock cores and wall rock toward mineral mapping and rock type classification, (2) improve the analysis of hyperspectral imagery for northern regions that are remote and difficult to access, and 3) to improve the analysis of hyperspectral data for boreal and tropical forests. Past research interests have included the use of Radar remote sensing for lithologic and structural mapping and the development of methodologies for precise measurement of emissivity.

Derek Rogge received his Ph.D. degree in 2007 at the Earth Observation Systems Laboratory, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada. Currently he is a research associate working in the Imaging Spectroscopy Laboratory at the University of Victoria, Canada. He has also been involved in collaborative projects with the Manitoba Geological Survey, Geological Survey of Canada, and the Institute for Aerospace Research, National Research Council of Canada. His current research is focused on the application of hyperspectral data for geologic mapping is the Canadian Arctic and the development of algorithms for improving image classification, specifically dealing with spectral unmixing and the integration of spatial and spectral information for mapping.

Liliana Sayuri Osako received a B.Sc. degree in geology from the São Paulo University (USP) in 1994, an M.Sc degree in metallogenesis from the State University of Campinas (UNICAMP) in 1999, and a Ph.D. degree for work on crustal evolution and lithogeochemistry from the Federal University of Pernambuco (UFPE) in 2005. She has work experience in management of spatial data, digital processing of remote sensing images, geophysics and GIS applications to geologic mapping, and mineral exploration. She is consultant in GIS on 1:100.000 geologic maps for joint programs between academia (São Paulo and Federal Ceará) and the Brazilian Geological Survey (CPRM). Dr. Osako is currently a postdoctoral researcher at the Federal University of Ceará, where her work involves the geologic and structural analysis of geophysical data (gravimetry and magnetometry) in tectonic domains of the Borborema province, northeast Brazil.

José Carlos Sícoli Seoane completed his B.Sc. (honors equivalent) at the University of São Paulo (USP, 1989) and D.Sc. at the State University of Campinas (Unicamp, 1999). He is currently adjunct professor IV at the Federal University of Rio de Janeiro (UFRJ), where he teaches GIS, photogeology, and remote sensing to undergraduate and graduate students. He has projects and ongoing collaborations with colleagues from several institutions in academia and the private sector, and has completed the supervision of six M.Sc. dissertations. He currently supervises five Ph.D. candidates and six final projects (honors equivalent). His main interests are the application of GIS, remote sensing and data integration to economic geology and exploration, geological cartography and marine geology. He is a member of the Coral Vivo Project steering committee and a reviewer for several periodicals as well as CNPq, Brazil's Research Council. He has worked eight years as a geologist, geochemist, and project leader for CVRD-Vale, and one year as the South America geochemistry exploration manager for Anglo Gold-Ashanti.

Carlos Roberto De Souza Filho received a B.A. degree in geological engineering from Ouro Preto Mines School, Brazil, in 1988, an M.S. degree in metallogenesis in 1991 from Campinas State University, Brazil, and a Ph.D. degree from Open University, England, in 1995. He has been on the faculty of Geosciences Institute of Campinas State University since 1997 and a full professor since 2002. Research interests have focused on mineral exploration, regional geology, metallogenesis, geotectonic, structural geology, remote sensing, spectroscopy, spectral geology and GIS.

James V. Taranik is the director of the Mackay School of Earth Sciences and Engineering at the University of Nevada, Reno. He is also Regents Professor and holds the Arthur Brant Endowed Chair of Exploration Geophysics at UNR. Dr. Taranik served as the president of the Desert Research Institute for 11 years and became president emeritus of DRI in 1998. He came to Nevada in 1982 as Dean of Mackay School of Mines and served in that capacity for five years. Prior to his Nevada move, Dr. Taranik was at NASA headquarters in Washington, D.C., where he was a branch chief in the Office of Space and Terrestrial Applications. At NASA he was responsible for NASA's geophysics and geology programs and was the chief scientist for the flight of the first scientific payload flown on the Shuttle. His career has included positions with the U.S. Geological Survey, the Iowa Geological Survey, and the U.S. Army as an officer in the Corps of Engineers in Vietnam. Dr. Taranik is a director of Newmont Mining Corporation. He received his B.Sc. degree in geology from Stanford University and his Ph.D. degree in geology from Colorado School of Mines.

Anne J.B. Thompson began her career in mineral exploration following an A.B. degree from Harvard University (1980) and an M.Sc. degree from the University of Toronto (1984). She completed typing her master's thesis in a caravan at the Teutonic Bore deposit, long before anyone dreamed of Hy-logger™. After 5 years in exploration throughout Australia and the SW Pacific, she carried out research in Utah on alunite. This work helped in the understanding of the effect of mineral composition on spectral responses. Anne established a consulting business in 1991 which focused on alteration and mineralogical studies. Through her company, PetraScience Consultants Inc., Anne provided petrographic, spectral, and other important mineralogical information for application to exploration, mining, and environmental projects around the world. Her extensive work using field spectrometers included case studies, establishing mineral references, training courses, and published papers. PetraScience closed in 2007, allowing Anne to take an extended sabbatical to pursue development and support of community sport for youth.

R. Greg Vaughan is currently an affiliate scientist with the Planetary Science Institute, Tucson, Arizona, and a USGS Mendenhall Postdoctoral Researcher at the USGS Astrogeology Science Center, Flagstaff, Arizona. In the previous three years he was a Caltech postdoctoral researcher at the Jet Propulsion Laboratory, Pasadena, California. His current research interests include the analysis and modeling of laboratory, field, and aerospace remote sensing data for surface compositional mapping and the application of quantitative remote sensing techniques to study dynamic geologic and environmental processes, with an emphasis on monitoring volcanic and geothermal phenomena. He earned a B.S. degree in geology in 1992 from Virginia Tech, Blacksburg, Virginia,, an M.S. degree in 1995 from the University of Georgia, Athens, Georgia, and a Ph.D. in 2004 from the University of Nevada Reno, Reno, Nevada.

Robert K. Vincent is a full professor in the department of geology at Bowling Green State University, which he joined in 1993. Before that, he was the founder and President of GeoSpectra Corporation and BioImage Corporation in Ann Arbor, Michigan. He holds a Ph.D. degree in geology from the University of Michigan, an M.S. degree in physics from the University of Maryland, and B.S. in physics and B.A. in math from Louisiana Tech University. He was a Landsat I Principal Investigator while at Willow Run Laboratories (now ERIM), at the University of Michigan, and he has written a text book entitled *Fundamentals of Geological and Environmental Remote Sensing,* Prentice Hall (1997), in addition to numerous other technical publications. He is a past director of the OhioView remote sensing consortium and past board member of the AmericaView remote sensing consortium. In 2004 he received Bowling Green State University's highest research honor, the Olscamp Research Award, for outstanding scholarly or creative accomplishments during the previous three years. He currently has environmental grants from the USDA for studying the effects of sewage sludge on agricultural fields in NW Ohio and from NOAA for mapping cyanobacterial blooms in Lake Erie from satellite. BGSU was awarded a patent on Nov. 7, 2006, for an algorithm he invented that uses Landsat TM data to map incipient cyanobacterial blooms in lakes. A new company is being spun off by BGSU and Dr. Vincent that will exploit the patent for monitoring drinking water reservoirs by satellite. An epidemiological paper (published by Archives of Environmental and Occupational Health) on which he is co-author has found mathematically significant health effects of humans living within one mile of agricultural fields that are permitted for Class B sewage sludge in Wood County, Ohio. Dr. Vincent also founded and is director of the Rotary District 6600 Global Satellite Water-Finding Office in the Dept. of Geology at Bowling Green State University.

Joe Zamudio received his Ph.D. degree in geology with an emphasis in remote sensing from the University of Colorado in 1992. His dissertation focused on geologic applications of hyperspectral remote sensing, using data from such sensors as the Airborne Imaging Spectrometer (AIS), and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). After receiving his degree, he worked at the U.S. Department of Energy's Remote Sensing Laboratory in Las Vegas, Nevada, where he was principal investigator for a project to evaluate hyperspectral remote sensing systems and their utility for environmental applications. Since 1995 he has been involved in various remote sensing projects for a variety of clients, working at various times for Analytical Imaging & Geophysics, Earth Search Sciences, and Applied Spectral Imaging, his own consulting company. During that time, he has been involved in the calibration of hyperspectral sensors, coordinating and planning hyperspectral surveys, and processing multispectral and hyperspectral data for a variety of geologic, environmental, and military applications. He has also taught workshops on basic and hyperspectral remote sensing for Research Systems Inc. (RSI), now ITT Visual Information Solutions.

DEDICATION

William P. Loughlin, 1952–2007

William Paul (Billy) Loughlin died suddenly of heart failure at the age of 55. Billy will be remembered by all who knew him as a great geologist, a great Irishman, and a great human being.

Billy was involved in remote sensing geology for many years, including some of the early Airborne Thematic Mapper scanner studies. He worked in mineral exploration in many parts of the world, with remote sensing as a tool. A pioneer and innovator with strong field-based skills, he had a penchant for keeping everyone he worked with thinking and entertained.

Nobody could ever doubt his passionate commitment to his chosen profession. Billy undertook extremely tough field assignments in South and West Africa, Ireland, and the United States and continually questioned the accepted wisdom within the often conservative world of mineral exploration. He was delighted to talk about geology everywhere and with everyone, although he sometimes made the mistake of assuming that all his listeners had energy and enthusiasm that matched his own.

In the field, with temperatures above 40°C in the Hijaz Mountains of Saudi Arabia, or below freezing in the snows of Utah, he was tireless in arguing his latest and often iconoclastic opinions, and relaxation in a pub or bar after work would usually find him at the center of an animated group. His realization of the potential of directed principal component analysis for simple and robust extraction of alteration zones from multispectral imagery, based on work by Crósta and others, was the high point of his time at the National Remote Sensing Centre, Farnborough, UK, and he startled the Defense Ministry physicists managing the Space Department with his impetuous and impassioned presentation of the technique and its possibilities.

Billy was in some ways almost archetypically Irish: red-haired, leprechaun-like of stature, a great talker ("the crack"), and passionate about music. His parents, either from a sense of humor or in an attempt to protect him in a sectarian society, christened him William (although they gave him Paul as a second name), but through the troubled times of the 1980s Billy suffered for his exuberant Irishness. British security officials, especially at airports, hassled him mercilessly, encouraged no doubt by his innate cockiness and mischievous sense of humour, and he once went missing for three days when detained as an IRA suspect at Heathrow on his way to Mozambique for geologic work.

Billy was also a wonderful human being, devoted to his family and friends, and held in happy affection by all who experienced his warmth and humanity. Billy and his wife, Lorraine, made a real home wherever they lived, and their home was always open to lucky visitors. He had a highly developed sense of justice, and his socialist principles were greatly enhanced during the Thatcher years in Britain. These principles were never in conflict with a strong entrepreneurial instinct, and he derived great pleasure from the challenge of turning a geologic hunch into a prospect and then a mine. All those who knew Billy reminisce about him with a broad smile. He had that effect on people.

Christopher Legg
Past Chief Scientist
National Remote Sensing Centre
Farnborough, UK

Preface

Remote Sensing and Spectral Geology

More than 25 years have elapsed since there was a special issue in *Economic Geology* on remote sensing (Goetz et al., 1983). With only a few spectral bands and large pixels, the major benefit of the only geologically meaningful satellite sensor at the time, Landsat Multispectral Scanner, was that it provided a new synoptic perspective of the Earth's surface. The spectral aspect of the science held promise, but the spectral resolution was very limited. Image processing focused mainly on the enhancement of texture for structural interpretation. Synoptic views led to the discovery of large structures and the pseudoscience of lineament analysis developed (e.g., Wise, 1982).

Today remote sensing technology and techniques have evolved to a point whereby it does not just indicate geology and alteration zones, but increasingly provides data that cannot be effectively mapped in any other way. In addition, remote sensing can directly contribute to the understanding of ore genesis. To be effective, it must be combined with field geology and other geologic methods, including geophysics, geochemistry, and other ancillary techniques such as field or laboratory spectroscopy.

The purpose of this Reviews volume is to combine reviews and case histories that will directly address the field geologist and other geoscientist specialists who would like to incorporate remote sensing in their work, whether it be for exploration or advancing geoscience knowledge.

This preface will summarize the content of the papers contained in this volume so the field geologist can use remote sensing techniques in a practical way as part of the mineral exploration process of mapping and economic discovery. For general background, two *SEG Newsletter* articles are reprinted as chapters 1 and 2. The first is a note in the *SEG Newsletter* by Eric Grunsky (2003), adding context to a recent paper on hyperspectral remote sensing in the journal of *Economic Geology*. This inspired a paper by Richard Bedell on "spectral versus spatial" resolution (2004). It became apparent that a basic explanation of the tradeoffs in spectral versus spatial resolution was important so that geologists could wade their way through the offerings of remote sensing and spectral data that were becoming available.

In addition, a classic and practical paper on field spectroscopy by Anne Thompson, Phoebe Hauff, and Anne Robitaille (1999), which had appeared earlier in the *SEG Newsletter*, is reprinted here as chapter 3. Prior to this article, field spectroscopy was generally not embraced as a standard tool in economic geology. This was because the science had to catch up and clearly demonstrate practical applicability in exploration. It took a number of detailed case studies with documented X-ray and petrographic studies, combined with accurate field context, to prove the utility of this technology. This study ran concomitantly with a growing understanding of hydrothermal systems, their sulfidation states, and associated alteration that allowed economic geologists to dissect them and explore them in unprecedented detail. The ability to be on an outcrop and have the context of the field while discerning a mineral phase is very powerful, particularly when so much of an alteration system can appear as a homogeneous mass or as an unzoned random mess to the naked eye. Anne Thompson used to say, before she wrote the article, that "there is nothing more dear to a geologist's heart than a mineral phase." We tend to agree with that statement because there are many parameters that can affect trace element geochemistry and geophysical properties, but a mineral phase has specific chemistry that has to reach stability to enable it to grow into a definitive crystal structure.

New background papers prepared specifically for this volume include updated reviews on spectral geology and the major satellite and airborne sensors. A review paper on spectral geology by Thompson, Scott, Huntington, and Yang (2009) offers more detail than the *SEG Newsletter* article, as well as showing some increased utility such as more effective core-logging capabilities. Field spectrometers are not just a useful adjunct to remote sensing; they are also an important tool in their own right for mapping outcrops, as well as drill core and reverse circulation drill chips. Many deposits have alteration halos and rapid, on-the-outcrop spectral results are very powerful for mapping and decision-making processes. Recent advances in hand-portable XRF units are a very useful adjunct to field spectrometers, as they provide increasingly rapid quantitative detection of trace elements and many metals with increasingly better detection limits. Combined with GPS and other geophysical techniques, our ability to collect corroborating quantitative field data is getting better all the time. These types of data superimposed on high-resolution remote sensing database offer unprecedented factual information for field mapping. Traditional formation mapping is not factual but largely interpretive. These quantitative tools provide lithologic and alteration phases through on-site mineral identification. More factual data for all geologic investigations are needed, and then the largely interpretive formation map can be added as an overlay.

A review of the classic Landsat series of satellites prepared by Crósta and Souza Filho (2009) does an excellent job of documenting the history and technology of these satellites, known as the "workhorse" of our industry. Landsat Thematic Mapper (TM) introduced the "clay band" in the mid 1980s and offered the ability to map argillic alteration. For a while this technology was oversold and many false anomalies resulted in a degree of skepticism within the mineral exploration industry. Having only one band in the clay region, it did not readily allow discrimination between hypogene alteration and other features, including vegetation, carbonates, sulfates, and supergene alteration. A variety of techniques were developed to overcome this limitation and, more importantly, it became obvious that a one-way process of providing data to the field without feedback and iteration to the

remote sensing specialist was not effective. This is one of the main purposes of this volume, to educate the field specialist to interact directly with the data and/or the people processing the data.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was launched in December 1999 as a joint United States-Japanese project and was designed for geologic applications. The clay region, or shortwave infrared (SWIR), contains five bands, providing the ability to map groups of clays and distinguish some sulfates and carbonates. More importantly, ASTER can distinguish argillic from advanced argillic, phyllic, and propylitic assemblages as well as calcite from dolomite. Shorter wavelength bands were designed to distinguish iron oxides and, in particular, jarosite can be distinguished from hematite and limonite. A major technical hurdle for ASTER is that it must be corrected to reflectance to determine these assemblages. There is no consistently effective method to do this—that the authors of this preface know—without getting ancillary data. This vastly limits the ability of the instrument to be used as a routine exploration tool. Alternatively, one can use the location on the image of known areas of mineralization and take the simple approach of "looking for more of the same thing." This requires a priori knowledge, but does not require correction to reflectance.

However, Crósta et al. (2009) presents a method by which ASTER can be used for alteration mapping without the need of atmospheric correction, by applying multivariate statistics. ASTER also provides five thermal bands, but the pixels are large and the signal to noise is poor. There is an ability to map silica and carbonates, but it is noisy and does not always work well. It is hoped that processing techniques will be developed to improve the ability to extract useful geologic information from its thermal bands.

Included here are several papers that employ the ASTER satellite including the following: Crósta et al. (2009), on mapping alteration related to precious metals in Patagonia; Perry and Vincent (2009), on lithologic mapping in Wyoming; Seoane et. al. (2009), on looking for Ni in Brazil; and Caceres et al. (2009), on mapping evaporates in Bolivia.

Taranik and Aslett (2009) provide a review of hyperspectral systems. This term simply means many near-contiguous bands as opposed to large discrete bands. Hypersectral sensors allow a remote sensing system to act more like a field spectrometer. However, as described in the article by Bedell (2004), the signal-to-noise ratio is only effective on airborne systems. The one experimental satellite hyperspectral sensor, Hyperion, is too far up in space to have a signal-to-noise ratio sufficient for practical exploration and mapping. Airborne hyperspectral systems can have excellent signal-to-noise because of the proximity to their target; however, mobilizing aircraft may make the costs prohibitive for large-scale grass roots exploration programs. The quality and cost of these surveys is continually improving and should be monitored as an effective exploration tool, particularly when regional commercial campaigns become available for mineralized districts. Hyperspectral data can provide maps of such continuous spectral detail that intense field mapping and field spectroscopy may not compete, but serve as an adjunct tool.

Thermal data is an underappreciated and underutilized exploration tool. The problem with thermal data is that the signal-to-noise ratio is so low at these longer thermal wavelengths (Bedell, 2004) that the detectors must be cooled and they are more expensive. However, the benefits for exploration and mapping are large, because one can map different types of silica, silicates, and carbonates. Taranik et al. (2009) provide a review of multispectral thermal data as it is used to map alteration, silica, and different igneous rock types. Not covered in this paper is the ability to use a single band of predawn thermal to map buried structures and rocks of high thermal inertia (such as jasperoid). An excellent example of using thermal remote sensing for exploration in Nevada can be found in Loughlin (1990).

One hyperspectral thermal system called SEBASS was developed by the Navy and is one of the tools described in Taranik et al. (2009). This system has become declassified and is currently available through Aerospace Corporation. As a result of the system, one can expect, in the near future, more exploration tools and methods that incorporate thermal data.

Data and Methods

The workhorse in our industry has changed from the Landsat TM, which allowed simple clay and iron oxide mapping, to the ASTER sensor that can assist in distinguishing groups of alteration assemblages such as argillic, advanced argillic, propylitic, and phyllic. Because these data are virtually free and readily available for most of the world, they have become a standard tool and are likely to be used for some time in the future, especially for frontier exploration regions.

Hyperspectral data is becoming increasingly available as well, and can determine many specific minerals as opposed to mineral groups. Because remote sensing data does not have the resolution of a lab or field spectrometer, one will encounter limitations of what can be resolved from the spectra. Because there are other features of the spectra besides the discrete absorption features, it is possible to infer minerals or mineral groups by general spectral shapes when combined with field work. Particularly with a multispectral system such as ASTER, for which there are six bands in the SWIR and optimally mixed combinations of minerals can produce a distinctive shape to the spectrum. With field checking one can gain confidence and infer the presence of a group of minerals without the spectral resolution necessary to map discrete and diagnostic absorption features.

For these data to be useful they need to be processed to derive certain spectral information or improve textural detail. For newer data, such as ASTER and hyperspectral imagery, there is an important preprocessing step that usually must be implemented for any kind of determinative processing. Data, as mentioned above, are reported as "radiance," meaning that the spectrum for each pixel has contributions from both the surface and the atmosphere. Therefore, these data need to be converted to reflectance by means of removing the contribution from the atmosphere, so that the spectra can be compared with spectral libraries. This is not a trivial task and is addressed in several of the papers. In addition, there is an Appendix 2, by Bedell and Coolbaugh (2009), with a brief explanation of the problems and a summary of the solutions using both model-driven and empirical methods. At the very

least, geologists using ASTER or hyperspectral imagery need to know that the data was converted to reflectance and how this was done.

Once the data are preprocessed, specialized images must be created. This step is usually accomplished with some type of classification method whereby a known mineral spectrum is searched for through the entire image. The ideal spectrum, called a "reference spectrum," may come from a preexisting spectral library or from the data itself. It is always better to train the classification (supervised classification) on data from the image, because it will be more representative of what can be found, and also because it will take into account any eventual flaw in the atmospheric correction preprocessing step.

Because of difficulties related to obtaining a good correction for reflectance, some scientists are taking the relatively raw "radiance" data to find areas of a known mineral on the image, and then using this area to classify the rest of the images. This is a very valid exploration method, but it requires prior knowledge of at least one area that is considered a favorable target. That requirement limits exploration to locating only what is known beforehand.

Appendix 1, prepared by Bedell and Crósta (2009), provides an introduction to basic image processing methods. Many graphics programs, such as those intended for manipulating digital photography, provide increasingly powerful image processing tools that allow geologists to take images and adjust them to suit specific geologic investigations. Real processing still requires sophisticated and dedicated software, but the more interaction geologists have with their data, the better. After all, an image provided by a consultant only contains a fraction of the actual information in the image. Thus, it is helpful for the geologist to know the basics of image processing to effectively work with the image-processing specialists by providing some of the information as well.

Case Studies

TM and ASTER alteration mapping gold systems in Patagonia

The paper by Crósta, Ducart, Souza Filho, Azevedo, and Brodie (2009) shows a comparison of alteration mapping using Landsat TM and ASTER data in an area within the rapidly emerging metallogenic provinces of southern Argentina. The Triassic-Jurassic volcanism that is associated with these precious metal deposits was a global-scale event that is now recognized as a Large Igneous Province (LIP) (http://www.mantleplumes.org/LIPClass2.html). The paper has good field mapping and field spectra to verify the quality of the alteration mapping interpreted from the Landsat and ASTER satellite data. Importantly, the paper walks the reader through how to dissect an eigenmatrix to select appropriate eigenvectors that have specific spectral features related to alteration minerals.

ASTER mineral mapping Ni laterite in Brazil

Seoane, Castro, Osako and Baars (2009) present their study of a nickel laterite exploration program working with digital topography derived from the space shuttle using RADAR (SRTM DEM data) along with the spectral recognition of nickel-bearing host rocks and nickel-bearing minerals using the SWIR and visible-NIR bands from ASTER mosaics. The method of feature-oriented principal component analysis (PCA) is used to produce predictive maps of mineral abundances. These mineral abundance images, when draped over the SRTM DEM data provide an enhanced view of the results for more effective interpretation.

Hyperspectral mapping of mineralized Mo-Cu systems in Colorado

Coulter, Hauff, Sares, Bird, Peters, and Henderson (2009) demonstrate the use of hyperspectral remote sensing for mapping a mineralized Mo-Cu porphyry system in Colorado through the spectral recognition of natural acid drainage response and leach-cap iron and clay minerals, which together form the alteration zone around the mineralization. Detailed mineral discrimination using hyperspectral responses shows the high level of detail to which the mineralized system and associated alteration can be mapped.

Mapping hydrothermal alteration through vegetation using Landsat in Brazil

Almeida, Souza Filho, Juliani, and Branco (2009) demonstrate the use of Landsat-5 TM data for mapping vegetation in virgin tropical rain forests of Brazil and the potential for recognizing differences in the vegetation that accompanies mineral alteration associated with an epithermal high-sulfidation gold deposit. This is accomplished through the application of spectral indices to enhance vegetation discrimination, the application of a two-stage PCA and a subsequent low-pass convolution filter.

Useful ASTER ratios for mineral mapping Powder River basin, Wyoming

Perry and Vincent (2009) have contributed a paper that extends what had been previously developed by Vincent (1997). The authors create a series of band ratios in ASTER that characterize specific rock types (limestone, red beds, sandstones, black shales) that assist in remote mapping. In addition, an extensive list of minerals is described along with the unique ASTER response signatures of those minerals.

Hyperspectral mapping of a skarn system, New Mexico

Zamudio (2009) presents an interesting case of an operational hyperspectral remote sensing application for precious metals at the El Capitan iron deposit, New Mexico. This is an iron-rich skarn with a later hematite-calcite alteration, with potential for Au, Ag, and Pt associated with the hematite-calcite alteration. The area has a considerable amount of vegetation, which complicates the use of remote sensing data. The author employed hyperspectral data from the 128-band Probe-1 airborne sensor, with support from field spectrometry data. He was able to identify anomalous areas of hematite-goethite, and calc-silicates that, after field checking, revealed anomalous gold and platinum values. Mineral mapping through hyperspectral data was quite effective in this case, yielding significant results in a timely manner, and thus saving time and costs in comparison with a thorough investigation in this vegetated terrain by geologists on the ground. The results obtained from hyperspectral data will guide future exploration efforts, including drilling.

Mapping in the Canadian Shield integrating TM and RADAR

Grunsky, Harris, and McMartin (2009) describe the combined use of multi-spectral Landsat TM and multibeam (Standard Beam 1/7, ascending-descending) RADARSAT-1 imagery for the classification of surficial materials in the Canadian north. Their approach uses spectral properties and the differential interaction of multibeam radar response, which serves as a proxy for surface roughness. They have applied this methodology using a supervised classification based on expert knowledge over limited areas from which regional predictive mapping can be carried out.

Mapping evaporites with ASTER in Bolivia

Caceres, Ali-Ammar, and Pirard (2008) describe an ASTER study in Bolivia to map evaporitic minerals. Many evaporitic minerals have diagnostic absorption spectra, particularly sulfates and borates. Carbonates also have diagnostic spectra and ASTER bands were chosen specifically to distinguish calcite from dolomite. This example of using ASTER is a good demonstration of how ASTER largely maps groups of minerals—not down to the species level because of its limited spectral resolution. In addition, the authors demonstrate a combination of empirical methods for correcting the data to reflectance and they compare results with previous mapping results. This is a useful paper on applying ASTER methodology regardless of the users' interest in mapping evaporitic assemblages.

Hyperspectral end-member mapping with Cu-Ni-PGE potential in the Canadian Shield

Rogge, Rivard, Harris, and Zhang (2009) present a study of using hyperspectral data from the Probe-1 instrument to map the Paleoproterozoic Trans-Hudson orogen on Baffin Island, Canada. It outlines a method of mapping lithology and the economic geology component identifies ultramafic and mafic complexes that could host Cu-Ni and PGE resources and iron oxide and argillic alteration for other potential economic mineralization. The paper outlines a method that extracts spectral end members and their relative abundances. Quantifying mixtures of end members in a pixel is difficult. Many authors assume it is a linear process, but it is not. Unmixing pixels is a highly nonlinear process with which they are trying to develop mapping techniques for the Geological Survey of Canada. Rogge et al. offer some new insights into this problem by reviewing the limitations of linear unmixing in a remote sensing context. They propose to limit the end members to only those that apply to one pixel. Therefore, they apply a two-stage process whereby one first identifies the end members for that pixel and then only use those in the linear unmixing process. Any multivariate technique can be improved by limiting the dimensionality of the problem and this is a practical application.

Core logging using thermal infrared

Cudahy, Hewson, Caccetta, Roache Whitbourn, Connor, Coward, Mason, Yang, Huntington, and Quigley (2009) demonstrate methodology that will be increasingly used as semiautomated core-logging with both spectroscopy and XRF instrumentation evolve. The baseline X-ray work must usually be done to orient this type of a survey. What is unique about this example is that the authors use the thermal infrared data, which is more expensive to acquire relative to the visible through SWIR spectrometers, but is important because it can map silica and silicates directly. In this case, for Archean gold deposits, albitization is an important proximal alteration assemblage. It is also important for IOCG and other types of mineralization. The example also shows mapping of carbonates related to mineralization but this can be routinely done using the less expensive SWIR spectrometers.

Summary

This collection of papers represents a cross section of activities that are currently being implemented in the mineral exploration community. Remote sensing technology will continue to emerge, to the benefit of the exploration community, through increased spatial and spectral resolutions. We hope that these papers will provide the necessary information and impetus to encourage the mineral exploration community to embrace these technologies for exploration advantage.

This volume does not address RADAR except briefly in the paper by Grunsky et al. (2009), where it is integrated in with other optical remote sensing data. RADAR can be a powerful remote sensing tool in exploration but it is fundamentally different than optical data and deserves a stand-alone volume.

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